

The sharp drop in the flux striking the Accretion Disk

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ABSTRACT

In this paper, We present a simple relativistic approach to analyze the flux striking the disk which is possibly from a source up the Black hole. The X-ray source is located above an accretion disc orbiting around the black hole, this assumption is invoked by recent studies about iron $K\alpha$. We compute and argue that due to the light bending effect near black hole, the flux striking the disk surface may be very concentrated, which will undoubtedly change the disk's ionization state hence change the iron line's ionization state and emissivity. Also, Our model may explain the steep power law when modelling the lines.

Subject headings: Fe $K\alpha$: AGN: emissivity: flux

1. Introduction

With the discovery of Fe $K\alpha$ emission at 6.4 keV and spectral hardening at 20–30 keV in the X-ray spectra of Seyfert 1 galaxies (Pounds et al. 1990), it was a center figure in probing the physics around black holes. ASCA's observation about the MCG-6-30-15's board and skewed profile reveal two important physical mechanisms—the gravitational and the Doppler effect. There are also other sources which show board and skewed profile. Various explanation and observation about the Fe $K\alpha$ have been presented (see fabian 2000, Reynolds & Nowak 2003 for details.) Another intriguing thing is that, the sources always show a X-ray continuum with power-law distribution, till now, there is no convincing explanation about the production of the X-ray continuum.

From both the observational and theoretical side, the iron line is expected to be the reflection from the accretion disk. A lot of computational method to compute the iron line profile from the vicinity of black hole has been invited (fanton 1997, Bromley 1994, labor 1991), among which the most renowned is the ray-tracing method due to its efficiency in computing. The differences in the line profiles from source to source have possibly implied variation in the

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geometry, the view angle, the structure of the BH-accretion disk system. With XMM's high S/N data, it greatly facilitates the astronomical community to study the iron $K\alpha$ in AGN. In order to model the Fe $K\alpha$, many detailed calculations about the accretion disk must be performed. Many authors have made computations considering the geometry, such as flat, concave, conical, thick. (Hartnoll 2002). Merloni found that the inner boundary condition of accretion flows has a significant effect on the profile. The ionization state and Fe abundance in the accretion disk also have been studied by Ballantyne 1999, Fabian 2002. Nayakshin's two-layer model in the surface of accretion disk also seems plausible. Recent MHD studies have proposed that there may exist spiral velocities in accretion disk which will bring quasi-humps in the profiles.

However, for simplicity, the disk emissivity is usually assumed to have a power-law profile $F(r) \simeq r^{-\alpha}$ (where $r = R/R_s = R c^2/2GM$ is the distance from the center in units of Schwarzschild radii), and the index of such power-law is generally assumed to be given by the accretion disk emissivity index in a standard geometrically thin and optically thick disk (Shakura & Sunyaev 1973). The fact that both Wilms et al. 2001 and Miller et al. 2002 require a larger value of α to fit the line profile has prompted speculation that, in the inner disk region, additional energy dissipation must be taking place. The long MCG-6-30-15's observation with XMM-Newton reported by Fabian et al. 2002 shows that the strong, skewed iron line is clearly detected and is well characterized by a steep emissivity profile within $6GM/c^2$ and a flatter profile beyond.

In contrast to explain the steep profile in the non-zero torque theory, which needs a comprehensive study of the MHD in accretion disk, we just make the simplest computation to deduce the flux striking the surface of the disk in the GR scheme, hence see the effects on line profiles, and the result is very useful in accounting for the steep emissivity in the inner part of the disk.

2. The model and computation

Numerical models of reflection spectra from accretion discs began with the simplest case: assuming a static, neutral and constant density slab of material irradiated by a power-law continuum of X-rays. George & Fabian (1991) and Matt, Perola & Piro (1991) performed Monte-Carlo calculations of the reflection spectra in such circumstances, and provided predictions on the equivalent width (EW) of Fe $K\alpha$ for different reflection geometries. In this paper, we also assume the source is centrally located, static with a power law flux $I_\nu = A \nu^{-\alpha}$, and this assumption is very close to the observation about the X-ray continuum.

the gravitational field of a rotating black hole is described by the Kerr metric (we use units $c=G=1$)

$$d s^2 = -(1 - \frac{2Mr}{\Sigma}) d t^2 - \frac{4M a r}{\Sigma} \sin^2 \theta d t d \phi + \frac{A}{\Sigma} \sin^2 \theta d \phi^2 + \frac{\Sigma}{\Delta} dr^2 + \Sigma d \theta^2 \quad (1)$$

where

$$\Sigma = r^2 + a^2 \cos^2 \theta \quad (2)$$

$$\Delta = r^2 + a^2 - 2M r \quad (3)$$

$$A = (r^2 + a^2)^2 - a^2 \Delta \sin^2 \theta \quad (4)$$

We can see that the metric depends only on two parameters, the mass M of the black hole and the specific angular momentum $a = J/M$. And it is straight forward to formulate that the photo in Kerr metric should have the relation in different place. We assume the photo propagate from place (r_1, θ_1) to place (r_2, θ_2) then we can get

$$\frac{\nu_1}{\nu_2} = \left(\frac{g_{00}(r_1, \theta_1)}{g_{00}(r_2, \theta_2)} \right)^{1/2} \quad (5)$$

and due to the invariance in general relativity

$$\frac{I_\nu}{\nu^3} = \text{const} \quad (6)$$

so we can deduce that

$$\frac{A_1}{\nu_1^{3+\alpha}} = \frac{A_2}{\nu_2^{3+\alpha}} \quad (7)$$

notice here, in the photons propagating in the Kerr metric, the A is changing, due to the frequency changing. so we can get

$$A_2 = A_{20} \left(\frac{g_{00}(r_1, \theta_1)}{g_{00}(r_2, \theta_2)} \right)^{(3+\alpha)/2} \quad (8)$$

as we know, in the newtonian space-time the intensity of the flux should not be changed, however, Eq. 8 shows that the intensity changed due to a factor. The same, we can get

$$F_{bending} = F_{straight} \left(\frac{g_{00}(r_1, \theta_1)}{g_{00}(r_2, \theta_2)} \right)^{(3+\alpha)/2} \quad (9)$$

where $F_{bending}$ is the flux striking the disc in Kerr metric, while $F_{straight}$ is the format in newtonian space-time. In the newtonian space-time. In the model of point like, static source up the black hole, the flux striking the disk should be

$$F_{straight} = \frac{L h}{4\pi (h^2 + r^2)^{3/2}} \quad (10)$$

in Kerr black hole,we know that

$$g_{00} = -(1 - \frac{2M r}{r^2 + a^2 \cos^2 \theta}) \quad (11)$$

we set r, a , in unit of m , then $F_{straight}$ can have the detailed formula

$$F_{bending} = \frac{L h}{4\pi (h^2 + r^2)^{3/2}} \left(\frac{1 - \frac{2h}{h^2 + a^2}}{1 - 2/r} \right)^{(3+\alpha)/2} \quad (12)$$

for a non-rotating black hole, we can get

$$F_{bending} = \frac{L h}{4\pi (h^2 + r^2)^{3/2}} \left(\frac{1 - 2/h}{1 - 2/r} \right)^{(3+\alpha)/2} \quad (13)$$

when we set r, h in unit of Schwchild radii $2M/r$, the formula change to

$$F_{bending} = \frac{L h}{4\pi (h^2 + r^2)^{3/2}} \left(\frac{1 - \frac{h}{h^2 + a^2}}{1 - /r} \right)^{(3+\alpha)/2} \quad (14)$$

from Eq. 14 we can see that the flux striking the accretion disc has a close relation with both the photo index α , the accretion rate a , and the sources location. Observations shows that the source X-ray continuum always have a photo index $\alpha \sim 2$.

when we compute the $F_{bending}$ in this model, we find that in a extremely rotating kerr metric the flux concentrated on only a very small region near the center, while other place left nearly no illumination at all. It is apparently a GR effect. when it comes to the schwchild metric, the power law approximation is also not good to describe the emissivity, but it is rather flatter to the case in Kerr Metric. We can conclude that the need of steep power law model may due to a rapidly rotating black hole.

3. Discussion

our work is invoked by recent report of steep emissivity in inner part of accretion disk (fabian 2002). In the observation of MCG-6-30-15, Fabian use a broken emissivity law to model the data, and with good result. However, they assume that the steep emissivity is a result from two reflector in the disk. In our work we can see that, the steep emissivity may come from the effect of light bending near the center black hole. And the concentrating of flux, will give inner side a rather high ionization parameter, ξ , which may result a line component at $\sim 6.8\text{keV}$. There are also other sources, such as IRAS 13224-3809 (Boller 2003), which should induce a steeper emissivity law. The steep emissivity law may be a evidence of a centering rapidly rotating black hole.

In present X-ray study, there are lots of uncertainty in modelling the iron lines in AGN, the S/N is a big problem to determine the real shape of the line. Former observation confirms that there exist many AGN which contain broad and skew iron line, indicating that the line is produced very near the black hole. However, recent XMM observation shows that there does not ubiquitously exist broad iron line, instead, a narrow core at 6.4 keV is present. This has not been included in this paper.

Our work shows that in the GR effect, the emissivity can not be simply regarded as a power law as a function of r , instead, it should be described by various factors such as a , the source's position, the photo index. When computed in the GR we find in the Kerr metric the large concentration of the flux in the accretion disc, rather than other part of the disk "empty", also, the large concentration in flux will undoubtedly invoke the model of ionized disk described by Ross 1999. And our work is only a simplified model to test the GR effects, further work such as the disk motion and density under high illumination which may affect the emissivity should be invoked.

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REFERENCES

- Ballantyne D.R., Fabian A.C., 2001, MNRAS, 328, L11
- Ballantyne D.R., Ross R.R., 2002, MNRAS, in press (astro-ph/0201420)
- Ballantyne D.R., Fabian A.C., Ross R.R., 2002, MNRAS, 329, L67
- Ballantyne D.R., Iwasawa K., Fabian A.C., 2001, MNRAS, 323, 506
- Ballantyne D.R., Ross R.R., Fabian A.C., 2001, MNRAS, 327, 10
- Boller Th., Brandt W.N., Fink H.H., 1996, A&A, 305, 53
- Branduardi-Raymont G., Sako M., Kahn S.M., Brinkman A.C., Kaastra J.S., Page M.J., 2001, A&A, 365, L140
- George I.M., Fabian A.C., 1991, MNRAS, 249, 352
- Fabian A.C., Vaughan S., Nandra K., Iwasawa K., Ballantyne D.R., Lee J.C., De Rosa, Turner, & Yound A.J., 2002 MNRAS
- Matt G., Perola G.C., Piro L., 1991, A&A, 247, 27

- Matt G., Fabian A.C., Ross R.R., 1993, MNRAS, 262, 179
- Matt G., Fabian A.C., Ross R.R., 1996, MNRAS, 278, 1111
- Matt G., Fabian A.C., Reynolds C.S., 1997, MNRAS, 289, 175
- Nayakshin S., Kallman T.R., 2001, ApJ, 546, 406
- Nayakshin S., Kazanas D., 2002, ApJ, 567, 85
- Nayakshin S., Kazanas D., Kallman T., 2000, ApJ, 537, 833
- Ross R.R., Fabian A.C., 1993, MNRAS, 261, 74
- Ross R.R., Fabian A.C., Young A.J., 1999, MNRAS, 306, 461
- Róžańska A., 1999, MNRAS, 308, 751
- Róžańska A., Czerny B., 1996, Acta Astronomica, 46, 233
- Shakura N.I., Sunyaev R.A., 1973, A&A, 24, 337
- Tanaka Y., et al., 1995, Nature, 344, 747
- Vaughan S., Pounds K.A., Reeves J., Warwick R., Edelson R., 1999, MNRAS, 308, L34

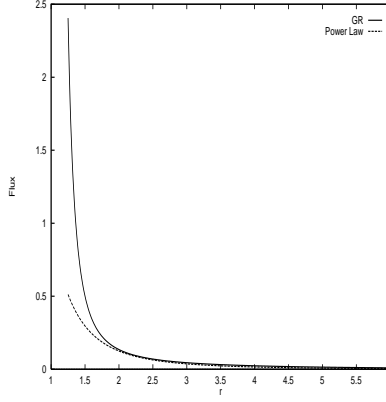


Fig. 1.— the flux striking the disk as a function of r , and a . In this picture, we set $h=5$, $a=0.998$, $\alpha=3$, $r_{in} = 1.24$, $r_{out} = 6$

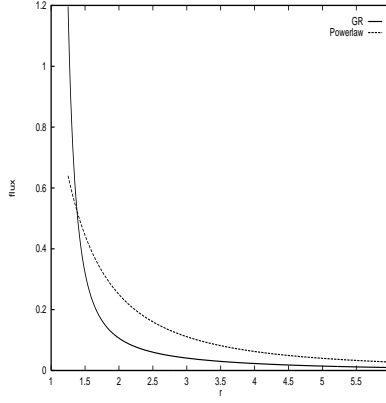


Fig. 2.— the flux striking the disk as a function of r , and a . In this picture, we set $h=5$, $a=0.998$, $\alpha=2$, $r_{in} = 1.24$, $r_{out} = 6$

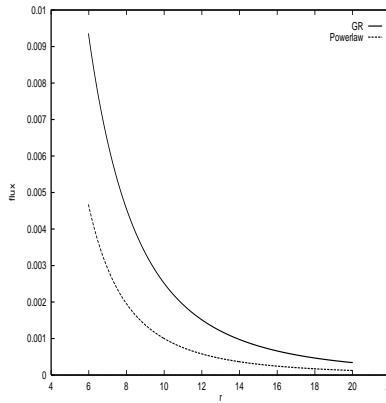


Fig. 3.— the flux striking the disk as a function of r , and a . In this picture, we set $h=5$, $a=0.01$, $\alpha=3$, $r_{in} = 5.97$, $r_{out} = 20$

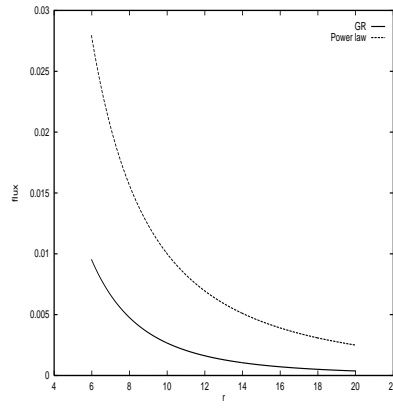


Fig. 4.— the flux striking the disk as a function of r , and a . In this picture, we set $h=5$, $a=0.01$, $\alpha=2$, $r_{in} = 5.97$, $r_{out} = 20$